Surgery from a Distance—Application of Intelligent Control for Telemedicine

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***Abstract*—Surgical robotics was only born three decades ago; however it has already spread out worldwide, resulting in systems that can provide less patient trauma and better medical outcome. In the near future, newly developed robotic systems may conquer even the most challenging fields—such as long distance telesurgery. While the master–slave (da Vinci type) robotic surgery practically means teleoperation from within the same room, NASA and other space agencies have long been focusing on its potential for long range applications. In the past decade, we have seen an amazing rise regarding the capability of surgical telepresence systems. Aiming to deploy telepresence technologies on a daily bases in the future, large communication latencies have to be dealt with. Telemedicine technologies offer a real solution to the climaxing problem of maintaining the quality of health care services in Europe. Radically new modeling techniques and algorithmic solutions have to be developed to make telemedicine more effective despite large communication delays. Besides appropriate manufacturing, adequate control strategies are required to ensure maximal effectiveness and safety. Currently leading teleoperated and hands-on systems have to solve major issues with system accuracy, force feedback and communication latency. Automated surgery is a technologically challenging area; it needs fine adaptation to the changing environment of the operating room. Modern control methods, such as model predictive control or soft computing alternatives are to be investigated in this paper, which are applicable to the problem of effective telesurgery. This technology could well find use in many other areas as well, from space exploration to remote mining and nuclear waste control.**

I. Introduction

The most dynamically emerging segment of robotic is service robotics. It is finding various applications for a wide range of uses from tourism to home care; however, medical robotics is becoming a leading domain. In Fig. 1., various areas of applications of this diverse field are presented, providing well known systems, as examples [1].

Robotic surgery is defined by the SAGES–MIRA Robotic Consensus Group [2] as "A surgical procedure or technology that adds a computer-technology-enhanced device to the interaction between the surgeon and the patient during a surgical operation, and assumes some degree of freedom of control heretofore completely reserved for the surgeon. This definition encompasses micro-manipulators, remotely controlled endoscopes and console-manipulator devices. The key elements are enhancement of the surgeon's abilities—by the vision, tissue manipulation, or tissue sensing—and alteration of the traditional direct local contact between surgeon and patient."

This incorporates smart tools and intelligent devices from hand-held cutters to remote telepresence systems. The broader field of technically aided interventional medicine is usually addressed as Computer-Integrated Surgery (CIS). It means the combination of innovative control algorithms, robotic devices, imaging systems, sensors and human–machine interfaces to work cooperatively with physicians in the planning and execution of surgical procedures [3].

II. Fundamentals of Telerobotic Surgery

Teleoperational surgical robots would provide an alternative to maintain the high quality of personal and medical care in Europe, where remotely operated devices would allow running the healthcare system at a much higher performance and cost-effectiveness. In order to reduce the performance degradation resulting from large latencies, the operator needs to be within the proximity of the remote site. This is the concept of teleoperation from within the human cognitive horizon [4]. Extending this horizon beyond a second is a key to improve the reach of effective telepresence.

Adequate controller design has a huge role ensuring high quality control signals and sensory feedback [5]. Aiming to design a suitable control scheme for the teleoperation scenarios introduced above, it is necessary to derive the applicable model of the human operator (master) and the robot (slave).

It can be assumed that the robot is a series of rigid links with typical mechanical properties, and the servo motors are driven by the local robot controller according to the control commands from the master side.

In telesurgery, it is desirable to minimize the load to the patient's tissue; therefore force control may be used [6]. Recent advancement in torque-controlled robotics, such as the commercially available KUKA LWR manipulator lead to the rise of new surgical robo-

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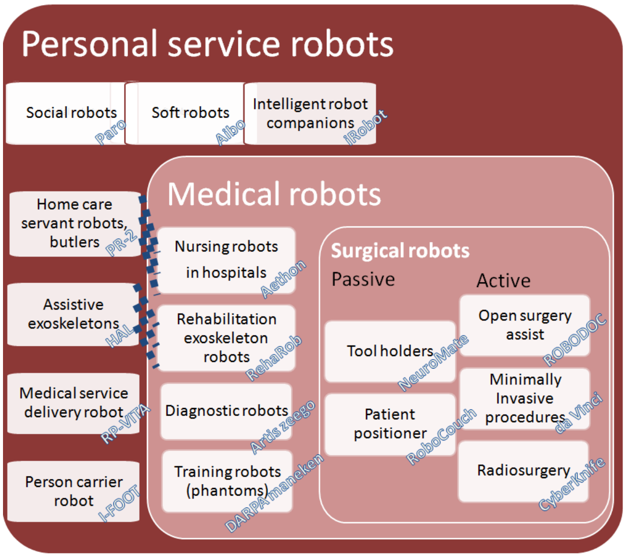

Figure 1. Categories of medical/non-medical personal service robots. Blue dashed lines indicate similar systems with different intended use. Existing commercial product and better-known prototypes are presented in light blue.

-tic setups. Examples include the ACTIVE EU FP7 project (*www.active-fp7.eu/*), the Amadeus system from the Canadian Titan Medical Inc. (*www.titanmedicalinc.com*), or the MiroSurge, a complete multi-manipulator system from the German DLR (*www.dlr.de/rm/en/desktopdefault.aspx/tabid-3835/6288_read-9047*).

Out of the many criteria towards telesurgical systems, stability and transparency have been considered to be the most important. Due to the fact that the robot–human–sensor triplet can be well delimited, an adequate method for control could be the design of a cascade controller [2].

Our project aims to develop a control system structure that would become a base-line solution to ensure high system performance within the framework of master–slave robot architectures.

The structure would handle the large time delays specific to communication of remote surgical robots. For this reason, not only classical control algorithms would be further developed, but also advanced Artificial Intelligence based methods. We are focusing on classical control options to provide a simple and universal solution [7].

Looking for a scalable solution, a naural selection is the cascade structure, where the data of the inner loop gives feedback to the outer loop, but no a priori knowledge about the inner loop's dynamics is required to design the outer controller. Moreover, it is possible to explicitly consider the remote dynamics in the outer controller in order to predict the inner behavior [8]. This can rely on the well-known Smith-predictor scheme or a similar one.

Based on the above requirements and assumptions, we proposed a cascade control structure employing empirical controller design to address the challenges of a system with large and probably varying latencies [2], [7], [9].

The use of empirical design methods is justified with the need for simple and quick algorithms, when model predictive control may be cumbersome to apply. In fact, with a master–slave setup a human physician controls the robot, and it is extremely difficult to develop plausible model for their behavior from the control point of view. It is important to identify the right model of each non/human controlled system component and to define the required parametric filtering enabling the smooth handling of the whole cascade structure.

III. Applications in Space

A large number of space experiments have been performed, and various setups developed to push the boundaries of teleoperation [10–12]. Different control schemes have been developed and tested to facilitate and enhance telepresence and to deal with issues such as transparency, bandwidth and latency [13–14].

In order to overcome the difficulties originating in signal latency, many ideas have been prototyped from predictive displays, supervisory control, passivity based control to wave variables and soft computing methods [6], [15-16].

While advanced internet-based communication theoretically enables telesurgery, serious challenges arise in the case of long distance operations or space exploration missions. Currently, it still seems inevitable to have a flight surgeon on board of the spacecraft for the proposed long term exploration missions, as robots do not have enough autonomy to adapt to unpredictable events.

With robot assisted surgery, a shared control approach should be followed, integrating high-fidelity automated functions into the robot to extend the capabilities of the human surgeon through image processing and force sensing [4].

This concept could be most beneficial for long duration on-orbit missions, primarily on board of the International Space Station (ISS). Teleoperational surgical robots would provide an alternative to human flight surgeons, where controller design has a huge role ensuring high quality control signals and sensory feedback [4].

In order to design a suitable control scheme for teleoperation scenarios introduced above, it is necessary to derive the applicable model of the human operator (master) and the robot (slave) [5]. It can be assumed that the robot is a series of rigid links with typical mechanical properties, and the servo motors are driven by the local robot controller according to the control commands from the master side. In telesurgery, it is desirable to minimize the load to the patient's tissue; therefore force control may be used [6].

In the past years, we performed a case study focusing on the compensation of latency and its effects. Three control algorithms were developed [9]:

- classical control using the empirical (extended) Kessler's method extended with the well-known Smith-predictor;
- soft-computing technique based on fuzzy control;
- model predictive control (MPC).

IV. RESULTS OF DIFFERENT CONTROL METHODS

The control methods were applied to a simulated cascade system for robotic telesurgery (Fig. 2) [17]. The outer (master) loop and the inner control were realized first by classical control using Kessler's empirical Extended Symmetrical Optimum (ESO) method [2], [18]. The reason of this was to provide a simple and scalable solution, and to deal with the disadvantages of empirical control to the outer loop.

In the case of classical control using Kessler's ESO method, we investigated the question of latency by the change of the ESO's tuning parameter β that represents the generalized parameter of the Symmetrical Optimum method [18]. We have shown in our case study that basically two optimal solutions can be achieved (Table 1) [17]. The first solution corresponds to the classical $\beta \in [4,16]$ situation, while the other to the $\beta \in [154,169]$ one (Fig. 3). The obtained result is much more theoretical as it reflects that a separate optimal solution can be achieved for fast systems (phase margin around 45°) and one for slow systems (phase margin around 60°). However, the practical applicability of the solution is limited as it could be efficient only for small latencies up to 2–3 sec.

Consequently, we have switched to modern control methods. First, we have tried soft-computing techniques, especially fuzzy control [19]. We have demonstrated that compared to the previous (classical control) solution, latency can be handled theoretically for even bigger values.

A Takagi–Sugeno–Kong PID–fuzzy controller was used which combines several (nine) separately designed PID controllers. The design and tuning method consisted on four steps involving the inner control loop where classical control method was applied [19]. The small number of rules in the fuzzy controller structure and the simplicity and transparency of the design and tuning method were the main advantages of the proposed approach. Results are presented in Fig. 4.

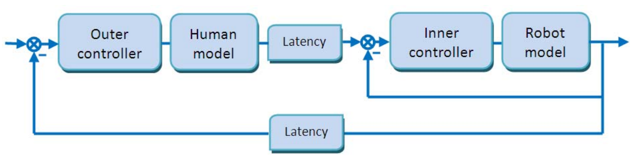

Figure 2. Simplified cascade structure for robotic telesurgery.

TABLE 1.

CONTROLLER PERFORMANCE PARAMETERS USING KESSLER'S ESO METHOD (T_D = 2sec).

β	Phase margin	Overshoot (σ)	Settling time (τ_t)
6	40.91°	26.42 %	2.60 s
9	**45.29°**	**25.49 %**	**2.59 s**
10	46.25°	24.71 %	2.75 s
14	49.05°	21.22 %	2.98 s
15	49.21°	20.38 %	3.04 s
16	49.42°	19.57 %	3.11 s
154	**56.22°**	**2.05 %**	**3.02 s**
160	56.28°	1.90 %	3.06 s
169	56.37°	1.70 %	3.10 s

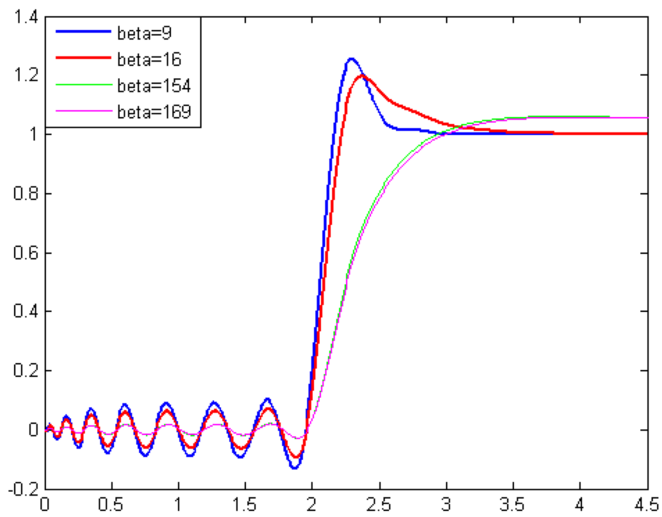

Figure 3. Kessler's method employed with Smith predictor for large latencies.

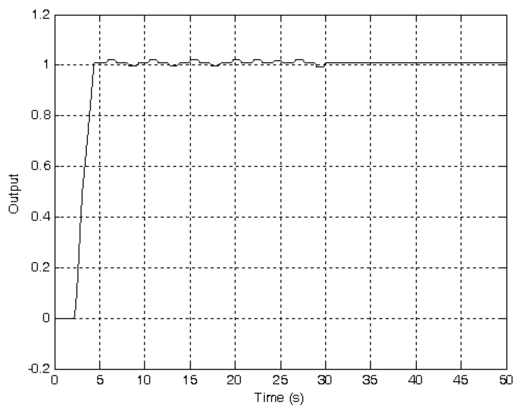

Figure 4. Result obtained by fuzzy controller for telesurgical application.

It can be seen that practically no overshoot was obtained while the settling time was considerably reduced as well (Fig. 4 vs Fig. 3). The improvement was obtained with only a small increase on the control signal energy part, but this can be easily satisfied in a telesurgical application environment where accuracy is much more important.

Finally, we moved on to MPC methodology, and investigated the critical factors of the modeled teleoperation system through simulations. We tested the system's response and quality characteristics (in terms of overshoot and settling time) with different values of latency in order to define the optimal parameter values of the MPC approach.

Our preliminary results demonstrated that the MPC structure could represent an ideal choice as it can handle the telesurgery system even in the large communication lag time range, where the previous solutions cannot provide anymore a stable response.

Based on its optimization criteria represented by its cost function, the aim of the MPC is to predict the change in the dependent variables of the modeled system; hence, this will be caused by changes in the independent variables as well.

The predictions on dependent variables are made on given N horizon and the predictions are calculated step-by-step, iteratively. The calculations are influenced by the horizon of the control signal N_c. As a result, MPC can be seen as a finite-horizon optimal control problem so that the control moves for the current time and a period of future time are obtained [20].

By a case-study, we have investigated the quality parameters of the system in function of N and N_c.

In the Earth–Moon distance (the time delay is $T_d = 2$ sec) results can be seen in Table 2.

It can be seen that the results are much better than those obtained by the classical control scheme. Iteration results for N = 23 and N = 30 are also presented in Fig. 5. We must not forget that the human operator's adaptation to the time delay as well as computing resources could limit its usability.

Hence, the use of modern robust approach will be examined in the future to generalize in terms of hard constraints the proposed approach applicability.

TABLE 2.

INFLUENCE OF N AND N_C FOR EARTH–MOON DISTANCE SCENARIO

	N	sup N_c	σ (%)	τt (sec)
1	21	2	11,13	4,5
2	23	3	1,27	2,63
3	23	5	0,1	2,63
4	**23**	**10**	**0,24**	**2,59**
5	25	3	1,76	2,73
6	30	5	2,43	2,73

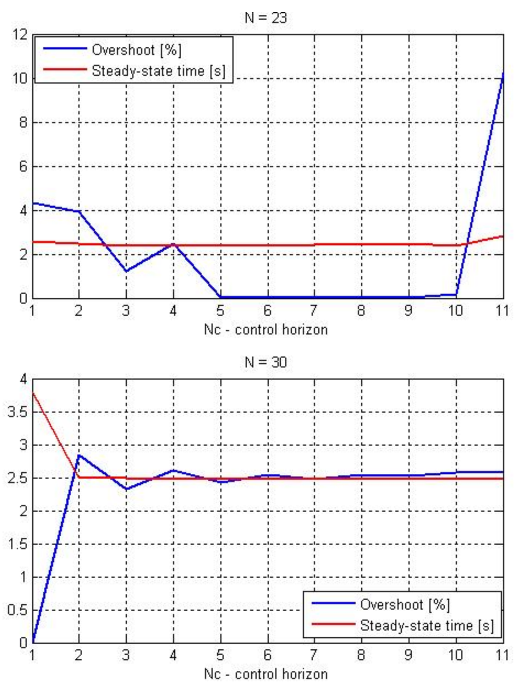

Figure 5. Iterative results of MPC algorithm for given horizon in case of an Earth–Moon distance scenario.

V. FUTURE WORK

In the future, we want to investigate and develop more advanced modern control algorithms, such as Generalized Model Predictive Control techniques. Several alternatives exist to superimpose the predicted robot model, such as the use of predictive video displays or augmented sensory fusion solutions [21]. The structure is suitable to include more complex models of the human later (e.g. fuzzy control model [22] or optimal control model [23–24]) and to achieve that the robot acquires a complete representation of the whole telesurgical scenario. We plan to investigate and to apply the numbered methods in the context of telesurgery.

External patient motion detection and compensation is a very important safety feature that would enable the safe use of patients in setups remotely located from the surgeon, where there is no opportunity for direct observation of the site.

A suitable concept to implement with these features is called Virtual Fixtures, where proximity sensing and tissue safeguarding is realized through simple mathematical algorithms. Automated bleeding reduction with coagulation will be developed based on the image segmentation method developed for brain tumor segmentation [25].

VI. CONCLUSION

Technology is having a major impact on modern health care. Innovative, automated safety features are soon to be realized on the robot slave side, including physiological organ motion compensation (which would be applicable to classical medical imaging, especially MRI-based diagnostics and treatment.)

Soon, medical robots can become pervasive for specific types of applications, including surgical robotics. Robots will be able to perform more complex procedures in teleoperation mode due to the fact that better control algorithms will provide more flexibility regarding latency management, and in the meanwhile, robots will be able to acquire knowledge, share it with humans or other robots, and to adapt to the local environment. This way, robots will be real partners of our future, leading to better and safer surgical care.

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REFERENCES

[1] G.S. Virk and T. Haidegger, "Classification Guidelines for Personal Care Robots—Medical and non-medical applications", in Proc. of the IEEE IROS Workshop on Safety in Human-Robot Coexistence & Interaction, Vilamoura, Portugal, pp. 33–36, 2012.

[2] T. Haidegger, *Theory and Methods to Enhance Computer-Integrated Surgical Systems*, PhD thesis, BME Budapest, 2011.

[3] R.W.J. Pease, *Medical Dictionary*, USA, Merriam–Webster, 2003.

[4] D. Lester, H. Thronson, Human space exploration and human space flight: Latency and the cognitive scale of the universe, Space Policy, 27(2), pp. 89–93, 2011.

[5] H. Bijl, *Human–Machine Systems, Summary*, Course materials, TU Delft, available: www.aerostudents.com, pp. 1–19, 2006.

[6] K. Kawashima, K. Tadano, G. Sankaranarayanan and B. Hannaford, "Bilateral teleoperation with time delay using modified wave variable based controller," in Proc. of the IEEE Int. Conf. on Robotics and Automation (ICRA), Kobe, Japan, pp. 4326–4331, 2009.

[7] T. Haidegger, L. Kovács, S. Preitl, R.E. Precup, B. Benyó and Z. Benyó "Controller Design Solutions for Long Distance Telesurgical Applications. International", *J. of Artificial Intelligence*, vol. 6, no. S11, pp. 48–71, 2011.

[8] P. Arcara and C. Melchiorri, "Control schemes for teleoperation with time delay: A comparative study", *Robotics and Autonomous Systems*, vol. 38, pp. 49–64, 2002.

[9] L. Kovács and T. Haidegger, "Telesurgery: a control theory approach", in Proc. of Computer Integrated Surgery Workshop, Budapest, Hungary, pp. 21–22, 2011.

[10] A. Rovetta, R. Sala, F. Cosmi, X. Wen, S. Milanesi, D. Sabbadini, A. Togno, L. Angelini and A.K. Bejczy, "A New Telerobotic Application: Remote Laparoscopic Surgery Using Satellites and Optical Fiber Networks for Data Exchange", *Intl. J. of Robotics Research*, vol. 15, no. 3, pp. 267–279, 1996.

[11] J. Rosen and B. Hannaford, "Doc at a distance," *IEEE Spectrum*, vol. 43, no. 10, pp. 34–39, 2006.

[12] H. King, T. Low, K. Hufford and T. Broderick, "Acceleration compensation for vehicle based telesurgery on earth or in space", in Proc. of the IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems (IROS), Nice, France, pp. 1459–1464, 2008.

[13] C. Passenberg, A. Peer and M. Buss, "A survey of environment-, operator-, and task-adapted controllers for teleoperation systems", *Mechatronics*, vol. 20, no. 7, pp.787–801, 2010.

[14] L.H. Eadie, A.M. Seifalian and B.R. Davidson, "Telemedicine in Surgery", *British J. of Surgery*, vol. 90, no. 6, pp. 647–658, 2003.

[15] M.P. Ottensmeyer, J. Hu, J.M. Thompson, J. Ren and T.B. Sheridan, "Investigations into Performance of Minimally Invasive Telesurgery with Feedback Time Delays", *Presence*, vol. 9, no. 4, pp. 369–382, 2000.

[16] J. Cui, S. Tosunoglu, R. Roberts, C. Moore and D. Repperger, "A review of teleoperation system control", in Proc. of the Florida Conf. on Recent Advances in Robotics (FCRAR), Dania Beach, Florida, USA, pp. 1–12, 2003.

[17] T. Haidegger, L. Kovács, H. Varga, S. Preitl, R.E. Precup, B. Benyó and Z. Benyó, "Extended Symmetrical Optimum Combined with Smith-predictor for Telehealth Applications: a Case Study", in Proc. of the 3rd Intl. Conf. on Recent Achievements in Mechatronics, Automation, Computer Sciences and Robotics (MACRo 2011), Targu-Mures, Romania, pp. 263–272, 2011.

[18] S. Preitl and R.E. Precup, "An extension of tuning relations after symmetrical optimum method for PI and PID controllers," *Automatica*, vol. 35, no. 10, pp. 1731–1736, 1999.

[19] R.E. Precup, L. Kovács, T. Haidegger, S. Preitl, A. Kovács, B. Benyó, E. Borbély and Z. Benyó, "Time Delay Compensation by Fuzzy Control in the Case of Master–Slave Telesurgery", in Proc. of the 6th Intl. Symp. on Applied Computational Intelligence and Informatics (SACI 2011), Timisoara, Romania, pp. 305–310, 2011.

[20] Bao-Cang D, *Modern predictive control*, CRC press, 2010.

[21] W. Kim and A. Bejczy, "Demonstration of a high-fidelity predictive/preview display technique for telerobotic servicing in space", *IEEE Trans. on Robotics and Automation*, vol. 9, no. 5, pp. 698–702, 1993.

[22] R. Hess, *Human-in-the-loop Control,* Chapter 12 in Control System Application, College Park, CRC Press, 1996.

[23] A. Phatak, H. Weinert, I. Segall and C.N. Day, "Identification of a modified optimal control model for the human operator", *Automatica*, vol. 12, no. 1, pp. 31–41, 1976.

[24] R.E. Precup and S. Preitl, "Optimisation criteria in development of fuzzy controllers with dynamics", *Engineering Applications of Artificial Intelligence*, vol. 17, no. 6, pp. 661–674, 2004.

[25] L. Szilágyi, *Novel image processing methods based on fuzzy logic*. PhD thesis, BME, 2008.